CERN-TH.7221/94

SEARCH FOR THE INVISIBLY DECAYING HIGGS PARTICLE AT LEP AND THE LHC

D.P. ROY
Theory Division, CERN, CH–1211 Geneva 23, Switzerland
and
Theoretical Physics Group, Tata Institute of Fundamental Research, Bombay 400 005, India*

Abstract

The Higgs particle can have dominantly invisible decay in a large class of Majoron models as well as some SUSY models. The LEP signal and mass limit for a Higgs particle undergoing invisible decay are explored. They are found to be very similar to those for the standard model decay. The best signatures and discovery limit for an invisibly decaying Higgs particle at the LHC are also discussed.

CERN-TH.7221/94
April 1994

(Invited Talk at the XXIXth Rencontres de Moriond on QCD and High Energy Hadronic Interactions, Méribel, France, 19–26 March 1994.)

*Permanent address

The signatures for Higgs particle detection at LEP and the future hadron colliders (LHC/SSC) have been extensively studied in the framework of the standard model (SM) and its supersymmetric (SUSY) extensions[1,2]. There exist some extensions of the SM, however, with a qualitatively different signature for the Higgs particle. These extensions are generically called the Majoron models (MM)[3–7] and have been quite popular, e.g. in the context of generating neutrino mass. They are characterized by the existence of a Goldstone boson (the Majoron). Since the coupling of this Goldstone boson to the Higgs particle is not required to be small on any theoretical or phenomenological grounds, the Higgs particle could decay into an invisible channel containing a Majoron pair[7–9]. Indeed the importance of extending the Higgs search to this invisible decay channel has been repeatedly emphasized over the past decade[8,9]. However, quantitative investigations along this line have only started very recently[10–12].

The key features shared by essentially all Majoron models is a spontaneously broken global $U(1)$ symmetry and a complex $SU(2) \times U(1)$ singlet scalar field η transforming non-trivially under the global $U(1)$. The spontaneous breaking of the global $U(1)$ generates a massless Goldstone boson, the Majoron $J \equiv \mathrm{Im}\ \eta/\sqrt{2}$, and a massive scalar $\eta_R \equiv \mathrm{Re}\ \eta/\sqrt{2}$. The latter mixes with the massive neutral component ϕ_R of the standard Higgs doublet through a quartic term $\phi^\dagger\phi\eta^\dagger\eta$ in the scalar potential. Thus one has two massive physical scalars

$$H = \cos\theta\phi_R + \sin\theta\eta_R \quad \text{and} \quad \mathrm{S} = \cos\theta\eta_\mathrm{R} - \sin\theta\phi_\mathrm{R}\ , \tag{1}$$

where the mixing angle can always be chosen to lie in the range 0–45°, so that the H and S have dominant doublet and singlet components respectively. The above quartic term also generates the following couplings of H and S to the massless Goldstone boson J :

$$\mathcal{L} = \frac{(\sqrt{2}G_F)^{1/2}}{2} \tan\beta \left[M_S^2 \cos\theta S J^2 - M_H^2 \sin\theta H J^2\right]\ , \tag{2}$$

where $\tan\beta = \langle\phi\rangle/\langle\eta\rangle$ is the ratio of the two vacuum expectation values[8]. The resulting decay widths of H, S into the invisible channel (JJ) relative to the dominant SM channel $(b\bar{b})$ are

$$\Gamma_{H\to JJ}/\Gamma_{H\to b\bar{b}} \simeq \frac{1}{12}\left(\frac{M_H}{m_b}\right)^2 \tan^2\theta \tan^2\beta \left(1 - \frac{4m_b^2}{M_H^2}\right)^{-3/2}\ , \tag{3}$$

$$\Gamma_{S\to JJ}/\Gamma_{S\to b\bar{b}} \simeq \frac{1}{12}\left(\frac{M_S}{m_b}\right)^2 \cot^2\theta \tan^2\beta \left(1 - \frac{4m_b^2}{M_S^2}\right)^{-3/2}\ . \tag{4}$$

The large mass ratio $(M_{H,S}/m_b)^2$ on the r.h.s. implies that the invisible decay channel could dominate for S as well as H over a large range of the parameters $\tan\theta$ and $\tan\beta$.[†]

Although eqs. (1)–(4) above were derived for the simplest model[3)] having 1 singlet and 1 doublet scalar fields, similar considerations hold for those having a larger Higgs content[5−8)] or a larger global symmetry group than $U(1)$[9)]. It may be added here that the Higgs particles can also decay invisibly in the SUSY models via a pair of lightest superparticles (LSP). For the minimal supersymmetric standard model (MSSM) this invisible decay mode has been shown to dominate only over a tiny range of parameters for the scalar Higgs particles but over a larger range for the pseudoscalar[13)].

Thus it is important to extend the Higgs search strategies at LEP and the LHC to cover the possibility of a dominantly invisible decay. This is simple at LEP, since the dominant channel for the Higgs search is the same for the SM and the invisible decays – i.e. the missing energy channel with one or two jets[10−12)]. It corresponds to the Bjorken production process

$$e^+e^- \xrightarrow{Z} Z^*H \tag{5}$$

followed by $Z^* \to \nu\bar{\nu}$, $H \to b\bar{b}$ for the SM decay and $Z^* \to q\bar{q}$, $H \to JJ$ for the invisible decay. Indeed the larger branching fraction of Z^* into quarks implies a larger event rate for the latter case. Figure 1 shows the expected number of signal events for the two cases[11)] for the ALEPH data sample of ref. [2]. The cuts reduce the signals by only a factor of $\sim 2/3$ in either case while completely eliminating the background. Thus the signal size for the invisible Higgs decay is a factor of 2–3 higher than the SM decay; and the corresponding 95% CL mass limit is higher by $\sim$ 6 GeV. This would imply an H mass bound somewhere between these two limits, depending on the relative size of the two decay models (eq. (3)). On the other hand the production cross-section (5) would be suppressed by a factor of $\cos^2\theta$ (≥ 0.5) since the Z couples only to the doublet component of the Higgs field. Combining the two effects leads to a M_H bound in the Majoron models, which is within ± 6 GeV of the SM value, irrespective of the model parameters, i.e. 48 ± 6 GeV [2,11)] going up to 60 ± 6 GeV with the new ALEPH data[12)]. A similar correlation between the Higgs signatures and discovery limits for the two models is expected to hold for LEP II as well. It may be noted that the dominantly singlet Higgs S

[†]Both parameters depend on the scale of the global $U(1)$ breaking relative to the $SU(2) \times U(1)$ breaking scale, on which there are no severe phenomenological constraints.

of the MM can be arbitrarily light for sufficiently small mixing angle θ, since the production cross-section is suppressed by a factor of $\sin^2\theta$.

At the LHC, the missing energy is not measurable in view of the large energy loss along the beam pipe. So one has to convert it into a missing-p_T ($\not{p}_T$) signature by looking at one of the following associated production processes at large p_T:

$$(i)\ H + \mathrm{jet}, \quad (ii)\ H + Z, \quad (iii)\ H + W \ \text{ and (iv) } \mathrm{H} + \mathrm{t}\bar{\mathrm{t}}\ , \tag{6}$$

followed by the invisible decay of H. While the first process has too large a background from $Z(\longrightarrow \nu\bar{\nu}) +$ jet, the second and third processes are expected to give viable signatures at the LHC[14]. Figure 2 shows the Higgs signal from (ii) along with the dominant background in the $\ell^+\ell^-\not{p}_T$ channel[14]. For $\not{p}_T > 200$ GeV, one gets a viable signal size (~ 2.5 fb) and signal/background ratio ($\sim 1/2$). Figure 3 shows the signal from (iii) along with the irreducible background in the $\ell\not{p}_T$ channel[14]. Here the signal size is ~ 5 fb and the signal/background ratio is ~ 1 for $\not{p}_T > 200$ GeV. Thus one should be able to probe the intermediate mass range of Higgs (100–200 GeV) even after making allowance for the suppression factor of $\cos^2\theta$ at the production vertex. For $M_H > 200$ GeV, the $H \to WW, ZZ$ decay modes are expected to dominate over the invisible (JJ) mode.

The fourth process has also been shown to give a signal/background ratio of ~ 1 at the LHC[16]. But the signal size is relatively small (~ 0.5 fb). Besides, this signal is far more demanding on the detector performance, as it requires good b identification as well as reconstruction of W and t masses from hadronic jets.

Finally, it may be noted that the signals of Figs. 1–3 are equally applicable to the invisible decay of Higgs scalar into a pair of LSP in the SUSY models. In fact they should be exact in this case since there is no singlet Higgs scalar S, i.e. $\cos\theta = 1$. However they do not apply to the pseudoscalar Higgs boson A of SUSY models, since it does not couple to gauge bosons. Only the last process mentioned above is applicable to the invisible decay of A [16].

References

1. See e.g. J.F. Gunion, H. Haber, G.L. Kane and S. Dawson, The Higgs Hunter's Guide (Addison-Wesley, Reading, MA, 1990).

2. ALEPH Collaboration : D. Decamp et al., Phys. Rep. **216** (1992) 253.

3. Y. Chikashige, R.N. Mohapatra and R.D. Peccei, Phys. Lett. **98B** (1980) 265.

4. D.B. Reiss, Phys. Lett. **115B** (1982) 217; F. Wilczek, Phys. Rev. Lett. **49** (1982) 1549.

5. G. Gelmini and M. Roncadelli, Phys. Lett. **B99** (1981) 411.

6. A.S. Joshipura and S.D. Rindani, Phys. Rev. **D46** (1992) 3000;
   A.S. Joshipura and J.W.F. Valle, Nucl. Phys. **B397** (1993) 105.

7. J.C. Romao, F. de Campos and J.W.F. Valle, Phys. Lett. **B292** (1992) 329.

8. R.E. Schrock and M. Suzuki, Phys. Lett. **B110** (1982) 250;
   L.F. Li, Y. Liu and L. Wolfenstein, Phys. Lett. **B159** (1985) 45;
   E.D. Carlson and L.B. Hall, Phys. Rev. **D40** (1985) 3187;
   G. Jungman and M.A. Luty, Nucl. Phys. **B361** (1991) 24;
   A.S. Joshipura and S.D. Rindani, Phys. Rev. Lett. **69** (1992) 3269.

9. J.D. Bjorken, Invited Talk at the Symposium on the SSC Laboratory, Corpus Christi, Texas, October 1991, SLAC-PUB-5673 (1991).

10. A. Lopez-Fernandez, J.C. Romao, F. de Campos and J.W.F. Valle, Phys. Lett. **B312** (1993) 240.

11. B. Brahmachari, A.S. Joshipura, S.D. Rindani, D.P. Roy and K. Sridhar, Phys. Rev. **D48** (1993) 4224.

12. ALEPH Collaboration : D. Buskulic et al., Phys. Lett. **B313** (1993) 312.

13. A. Djouadi, J. Kalinowski and P.M. Zerwas, Z. Phys. **C57** (1993) 569.

14. Debajyoti Choudhury and D.P. Roy, Phys. Lett. **B322** (1994) 368.

15. M. Diemoz, F. Ferroni, E. Longo and G. Martinelli, Z. Phys. **C39** (1988) 21.

16. J.F. Gunion, Phys. Rev. Lett. **72** (1994) 199.

Figure captions

Fig. 1 The expected Higgs signals for the SM and MM (invisible) decay modes corresponding to the published ALEPH data[2)].

Fig. 2 The HZ signal (dotted and dashed lines) and the ZZ background (solid line) cross-sections for the dilepton + missing-p_T channel at the LHC, calculated using the DFLM structure functions[15)].

Fig. 3 The HW signal (dotted and dashed lines) and the WZ background (solid line) cross-sections for the lepton + missing-p_T channel at the LHC, calculated using the DFLM structure functions[15)].